(19) Europäisches Patentamt
European Patent Office
Office européen des brevets

(11) Publication number: 0 125 137 B1

(12) EUROPEAN PATENT SPECIFICATION

(45) Date of publication of patent specification: 22.08.90

(51) Int. Cl.[5]: C 12 M 1/40

(21) Application number: 84303087.5

(22) Date of filing: 08.05.84

(54) Measurement of enzyme-catalysed reactions.

(30) Priority: 05.05.83 GB 8312259
29.02.84 GB 8405262
29.02.84 GB 8405263

(43) Date of publication of application:
14.11.84 Bulletin 84/46

(45) Publication of the grant of the patent:
22.08.90 Bulletin 90/34

(84) Designated Contracting States:
BE CH DE FR GB IT LI NL SE

(56) References cited:
EP-A-0 025 110
EP-A-0 048 090
EP-A-0 078 636
EP-A-0 078 636
US-A-4 224 125
US-A-4 233 144
US-A-4 293 310

(73) Proprietor: MediSense, Inc.
128 Sidney Street
Cambridge Massachusetts 02139 (US)

(72) Inventor: Higgins, Irving John
Lion Fields Barford Road
Welden Bedford MK43 2QG (GB)
Inventor: Hill, Hugh Allen Oliver
9 Clover Close
Oxford OX2 9JH (GB)
Inventor: Plotkin, Elliot Verne
14 George Street
Bedford MK43 SG (GB)

(74) Representative: Clifford, Frederick Alan et al
MARKS & CLERK 57/60 Lincoln's Inn Fields
London WC2A 3LS (GB)

EP 0 125 137 B1

Courier Press, Leamington Spa, England.

Description

This invention relates to equipment and methods for detecting the presence of, measuring the amount of, and/or monitoring the level of, one or more selected components in a liquid mixture.

While use may be made of this invention in chemical industry, especially where complex mixtures are encountered (e.g. in food chemistry or biochemical engineering) it is of particular value in biological investigation and control techniques. More particularly, it lends itself to animal or human medicine, and in particular to *in vivo* measuring or monitoring of components in body fluids. The provision for sensors of components in biological fluids is one object of the invention.

In vivo glucose sensors have already been proposed. One proposal is based on direct oxidation of glucose at a catalytic platinum electrode (see Hormone and Metabolic Research, Supplement Series No. 8, pp 10—12 (1979)) but suffers from the drawback of being non-specific and of being easily poisoned by interfering substances. Another proposal, for a procedure more specific to glucose, involves the use of glucose oxidase on an oxygen electrode (Adv. Exp.Med.Biol. *50* pp 189—197 (1974)) but is not very responsive to the high glucose concentrations. Other systems using glucose oxidase have been proposed but not fully investigated for *in vivo* methods, see e.g. J. Solid-Phase Biochem. *4* pp 253—262 (1979)).

Our European Patent Application 82305597 (EP—A—78636) describes and claims a sensor electrode composed of electrically conductive material and comprising at least at an external surface thereof the combination of an enzyme and a mediator compound which transfers electrons to the electrode when the enzyme is catalytically active.

The purpose of such an electrode is to detect the presence of, measure the amount of and/or monitor the level of one or more selected components capable of undertaking a reaction catalysed by the said enzyme.

Examples of electrode configurations, mediators and uses are given in that patent application.

The present invention is based on the realisation that one particular class of mediator compound exemplified in EP—A—78636 has a general utility as a mediator for a wide range of enzymes.

The inventors have carried out *in vitro* studies of enzyme-catalysed reactions using a mediator in solution to transfer the electrons arising from the enzyme, during its action, directly to the electrode, as described in Biotechnology Letters *3* pp 187—192 (1981).

There have been numerous other attempts to find satisfactory mediators for enzyme-catalyzed electrode systems. Just a few examples of such attempts are: Mindt *et al.* U.S. Patent 3,838,033; Nakamura *et al.* U.S. Patent 4,224,125; Hawkridge *et al.* 4,144,143; and Suzuki *et al.* 4,388,166.

Generally it is desirable to find a mediator which meets the particularly stringent demands of quantitative electrochemical assaying.

We have discovered that a class of mediating compounds has extremely useful properties for mediating enzyme-catalysed reactions in electrode sensing systems. Specifically, the invention features, as electrode sensor mediators, organometallic compounds composed of at least two organic rings, each of which has at least two double bonds in a conjugated relationship; a metal atom is in electron-sharing contact with those rings. The mediators are broadly useful in electrode sensor systems having two conductors insulated from each other, each of which is in contact, via a conductive surface, with a mixture of compounds that includes the selected compound to be sensed. An enzyme capable of catalyzing a reaction at a rate representative of the selected compound concentration is in contact with the mixture, and the mediator compound transfers electrons between the enzyme and the conductive surface of one of the conductors at a rate representative of the enzyme catalyzed reaction rate.

In the present invention, the mediators are predominantly ferrocene-type compounds, however, ruthenocene type compounds are also envisaged as mediators. The enzyme is a non-oxygen specific flavo-protein other than glucose oxidase, a quinoprotein other than glucose dehydrogenase, a haem-containing enzyme, a cupro-protein, or carbonmonoxide oxidoreductase.

As noted above, a particularly preferred form of mediator compound is a ferrocene or ferrocene derivative.

Ferrocene, has, as its fundamental structure, an iron atom held "sandwiched" by dative bonds between two cyclopentadienyl rings. It is an electroactive organometallic compound, acting as a pH-independent reversible one-electron donor. Various derivatives are available (e.g. with various substituents on the ring structure, possibly in polymer form) differing in redox potential and aqueous solubility.

For instance, the redox potential of the parent compound is +420 mV vs NHE. By introducing functional groups on to the ring system, $E^{o'}$ can be varied between +300 and +650 mV. Moreover, the water-solubility of the carboxyl-substituted ferrocenes is greater than that of the parent compound. Further description will be found in Kuwana T. *et al.*, 1977, ACS Symposium Series, 38, 154.

Among specific mediator compounds of this type are ferrocene itself, 1,1'-ferrocene dicarboxylic acid, dimethyl ferrocene, and polyvinyl ferrocene, e.g. of average molecular weight of about 16000.

The demands placed on the mediator are particularly stringent. Preferably the mediator readily shuttles electrons between the enzyme and the conductive electrode surface at a rate that is high enough to render potentially conflicting reactions insignificant. The response rate should therefore be rapid. Moreover, the response should cover as large a region as possible, to enhance the precision of the concentration reading. The mediator should be concentrated at the electrode surface in sufficient

concentration to accomplish electron transfer. Where the mediator is covalently bound to the electrode and/or the enzyme, the bonding must not interfere with the mediating function. The mediator therefore should be relatively insoluble in most applications. It should be stable and non-responsive to interfering substances such as oxygen or pH. Most importantly, however, the rate of electron transfer must be dependent on the rate of the enzyme-catalyzed reaction. That is, the mediator must effect electron transfer during the period of catalytic activity at a rate representative of that activity.

Satisfactory performance in the above-listed areas is obtained with ferrocene-type compounds in an extraordinarily broad range of sensor systems. For example, ferrocene can mediate electron transfer for a broad range of enzymes.

1,1'-dimethylferrocene is a particularly preferred mediator. The selected component to be sensed is preferably the substrate for the enzyme-catalyzed reaction. Also, preferably, the enzyme and/or the mediator are confined at the conductive surface of one of the conductors. Finally, in preferred systems, the mediator transfers electrons from the enzyme to the electrode surface. The properties of a range of ferrocene derivatives, together with those of the parent compound are given in the table below;

TABLE 1

Ferrocene derivative	E°	Solubility
1,1'-dimethyl-	100	I,D
acetic acid	124	S
hydroxyethyl-	161	S
ferrocene	165	I,D
1,1'-bis(hydroxymethyl)-	224	S
monocarboxylic acid	275	S
1,1'-dicarboxylic acid	385	S
chloro-	345	I,D
methyl trimethylammonium salt	400	S

S indicates water solubility; I,D means respectively insoluble and detergent solubilised in 3% Tween-20. E° is in mV vs a standard calomel electrode.

The E° values of various ferrocenes in phosphate buffer at pH 7.0 given in the above table, span a range of potentials, E° = 100 to 400mV vs SCE. The trend in E° values is in agreement with that expected on the basis of substituent effects. In general electron-donating groups stabilize the positive charge and hence promote oxidation more so than electron withdrawing groups.

The electrically conductive material of the electrode itself can be a metal, particularly silver, or carbon either as a pre-formed rod or as an electrode shape made up from a paste of carbon particles or as a carbon fibre. Surface condition of the electrode is usually important. If metal, the surface can be roughened where it contacts the active materials (enzyme and/or mediator). If solid carbon, the surface can be "oxidised" i.e. previously heat-treated in an oven with oxygen access.

Certain combinations of the above materials, and certain configurations of electrode, are preferable in practice.

Optionally, enzyme immobilisation materials, or polymeric electrode admixtures e.g. TEFLON (Trade Mark), or long-chain alkyl derivatives of mediators of increased molecular weight and thus decreased mobility, can be incorporated.

The carbon core for the electrode can itself be solid or a stiff paste of particles or as a carbon fibre. Normally, it will present a smooth surface for the ferrocene or ferrocene derivative, which may be adhered thereto in a number of ways, for example,

(a) For a monomeric ferrocene or ferrocene derivative, by deposition from a solution in a readily evaporatable liquid e.g. an organic solvent such as toluene.

(b) For a ferrocene polymeric derivative, deposition from a readily evaporable organic solvent for the polymer such as chloroform. J. Polymer Sci. 1976. *14* 2433 describes preparation of a polyvinyl ferrocene of average molecular weight about 16000 which can be deposited in this way.

(c) For a polymerisable ferrocene-type monomer, by electrochemically induced polymerisation in situ, e.g. by dissolving vinyl ferrocene in an organic electrolyte containing tertiary butyl ammonium perchlorate

in concentration about 1mM and depositing at a potential of — 700 mV vnyl ferrocene radicals as a polymer in situ.

(d) By covalent modification of the carbon electrode e.g. by carbodiimide cross-linking of the ferrocene or ferrocene derivative on to the carbon.

Other methods of immobilisation, or other forms of protection e.g. incorporated into a self-supporting gelatine layer, are also possible.

Optionally, but preferably when being used on whole blood, a protective membrane surrounds both the enzyme and the mediator layers, permeable to water and substrate molecules. This can be a film of dialysis membrane, resiliently held e.g. by an elastic O-ring. It can however also with advantage be a layer of cellulose acetate, e.g. as formed by dipping the electrode into a cellulose acetate solution in acetone, or polyurethane membranes may be applied by spray, dip or spin coating techniques.

It will be apparent that while the invention has primary relevance to a sensor electrode, it also relates to the combination of such an electrode and temporary or permanent implantation means, e.g. a needle-like probe. Also, such an electrode, connected or connectable, with signal or control equipment, constitutes an aspect of the invention.

The electrodes of the invention, on the macro-scale could be incorporated into simple, cheap electronic digital read-out instruments for doctors' surgeries or diabetic home-testing kits.

Use of a small version of the macro-sensor would be possible in a device which automatically takes a blood sample from the finger, brings it into contact with the sensor, amplifies the signal and gives a digital readout.

The enzymes that can be used with ferrocene-mediated systems include: flavoproteins that are capable of using a variety of electron acceptors, including oxygen; and NADPH-or NADH-linked enzymes such as lipoamide dehydrogenase and glutathione reductase; dehydrogenase enzymes, termed quinoproteins, that contain the pyrroloquinoquinoline group (PQQ). The use of glucose oxidase or glucose dehydrogenase is excluded, in view of EP—A—78636.

A listing of flavoproteins that generate H_2O_2 appears in Clark et al. Biotechnol. Bioeng. Symp. *3*:377 (1972). Particularly preferred flavoproteins are: pyruvate oxidase, xanthine oxidase, sarcosine oxidase, gycolate oxidase, L-amino acid oxidase.

Suitable quinoproteins include methanol dehydrogenase. A list of PQQ quinoproteins appears in Duine *et al.* TIBS *6*:278(1981).

Finally, haem-containing enzymes can be used in ferrocene-mediated electrode systems. Such enzymes include: horseradish peroxidase, yeast cytochrome c peroxidase, lactate dehydrogenase i.e. yeast cytochrome b_2.

The compatibility of an enzyme such as those listed above with ferrocene can be demonstrated using d.c. cyclic voltammetry in which current at a working electrode is measured over voltage sweeps.

The current measured includes a Faradaic component which results from electron transfer to and from an electro-active species in the solution. If the rate of electron transfer between the electro-active species is sufficiently fast, the Faradiac current is controlled by the rate of diffusion of the electro-active species. The enzyme-catalyzed reaction causes a perturbation in the voltammogram that depends on the reaction rate, compared with the time required for the voltage sweep.

Thus, the suitability of a particular mediator for transfer between a particular enzyme and an electrode can be assessed as described below in examples 12—28.

The preferred enzymes are the flavo-protein enzymes which are not oxygen-specific and the quino-protein enzymes, apart from glucose oxidase or glucose dehydrogenase.

As discussed above, in the preferred sensor system the compound selected to be measured is the substrate for the enzyme, and the enzyme and mediator are confined at the electrode surface. The electrode is exposed to a mixture containing the selected compound, and the enzyme becomes catalytically active, generating a current representative of the compound's concentration.

Other configurations are possible, however, in which the rate of the enzyme catalyzed reaction is a surrogate for the concentration of another compound that is not the enzyme substrate.

The invention is illustrated by the following Examples 12 to 25. The invention as now claimed does not extend to the possibility that the enzyme is glucose oxidase or glucose dehydrogenase. Such enzymes are specifically mentioned in EP—A—78636. Examples 1 to 11 and 26 to 31 relate to these enzymes, and are retained for their disclosure relevant to the performance of the present invention.

Figure 1 shows a circuit which may be used for d.c. cyclic voltammetry;

Figure 2 shows a two-compartment cell for d.c. cyclic voltammetry;

Figure 3 is a FPLC profile of co-oxidoreductase from *Pseudomonas thermocarboxydovorans,* and

Figure 4 is a voltammogram of carboxyferrocene;

Comparative example 1

Purification of Quinoprotein Glucose Dehydrogenase (GDH) from *Acinetobacter calcoaceticus*

(a) Growth of Organisms

Strain NTCC 7844 was grown on sodium succinate (20 gl^{-1}) in batch culture at pH 8.5 and 20°C. Cells were harvested after 20 hours (A_{600}=6.0) using a Sharples centrifuge, and stored frozen.

(b) Purification of Glucose Dehydrogenase

The method is based on the method of J. A. Duine *et al* (Arch Microbiol, 1982 vide supra) but with modifications as follows.

1. 100 g of cells were thawed, resuspended in 300 ml of 56 mM Tris/39 mM glycine and treated for 20 minutes at room temperature with 60 mg lysozyme.

2. Triton X—100 extracts were combined and treated with 0.01 $mgml^{-1}$ of deoxyribonuclease I for 15 minutes at room temperature. The resulting suspension was then centrifuged at 48000 g for 25 minutes at 4°C. The supernatant from this centrifugation was then treated with ammonium sulphate. The yellow protein precipitating between 55 and 70% ammonium sulphate was resuspended in 36 mM Tris/39 mM glycine containing 1% Triton X—100 and dialysed against that buffer at 4°C for 5 hours.

3. Active fractions from the CM Sepharose CL—6B.

Column eluants were combined and concentrated using Millipore CX—30 immersible ultrafilters.

Comparative example 2

Purification of Quinoprotein Glucose Dehydrogenase from *Acinetobacter calcoaceticus* (alternative method)

(a) Growth of Organisms

The method of Example 1 was repeated.

(b) Purification of GDH

The method is based on the partitioning of proteins between two liquid phases. The steps were:

1. Cells were thawed and resuspended at 3 ml/g wet weight in 50 mM sodium phosphate, pH 7.0. They were then pre-cooled on ice and passed once through a Stansted presure cell (made by Stansted Fluid Power Ltd., Stansted, Essex, UK) at 25000 psi. This provides the cell-free extract.

2. The cell-free extract was then mixed for 15 minutes at room temperature with 50% (w/v) polyethyleneglycol 1000, 50% (w/v) sodium phosphate, pH 7.0 and distilled water in the proportions of 2:4:3:1 respectively. This mixture was centrifuged at 5000 rpm for 5 minutes to break the emulsion.

3. The lower layer was aspirated off and desalted immediately, by either diafiltration using an Amicon hollow-fibre ultrafiltration cartridge of 10000 mwt cut off, or by passage through a Sephadex G50 (medium grade) gel filtration column.

4. The resulting solution was concentrated using an Amicon PM10 membrane in a nitrogen pressure cell.

Comparative example 3

Interaction between ferrocene and glucose oxidase

DC cyclic voltammetry was used to investigate the homogeneous kinetics of the reaction between ferrocene and the glucose oxidase enzyme under substrate excess conditions. A two compartment electrochemical cell of 1.0 ml volume fitted with a Luggin capillary was used. The cell contained a 4.0 mm gold disc working electrode, a platinum gauze counterelectrode and a saturated calomel electrode as a reference. A series of voltammograms for ferrocene was recorded at scan rates of 1—100 mVs^{-1} in 50 mM potassium phosphate buffer, pH 7.0. The data show that the mediator acted as a reversible, one-electron acceptor $E^{o\prime} = +165mV$ vs. SCe.

Addition of 50 mM glucose has no discernible effect on the electochemistry of the mediator (500 µM). Upon addition of glucose oxidase (10 µM), however, an enhanced anodic current was observed in the voltammogram at oxidising potentials with respect to the mediator. This indicated catalytic regeneration of the reduced form of the mediator by glucose oxidase. Quantitative kinetic data were obtained for this reaction using an established procedure (Nicholson, R. S. and Shain, I., 1964, *Anal. Chem., 36, 707).* The mediator gave a second order rate constant for the reaction between ferricinium ion and reduced glucose oxidase of $K = 10^4 M^{-1}s^{-1}$. This ability of the ferricinium ion to act as a rapid oxidant for glucose oxidase facilitates the efficient coupling of the enzymic oxidation of glucose.

Comparative example 4

The procedure of Example 3 was repeated using 1,1'-ferrocene dicarboxylic acid instead of ferrocene. The value of $E^{o\prime}$ was determined to be +420 mV, and the second order rate constant of the ferricinium ion and reduced glucose oxidase was again $10^4 M^{-1}s^{-1}$, thus confirming the conclusions drawn from Example 3.

Comparative example 5

Glucose Oxidase/1,1'-Dimethyl Ferrocene

Mini electrode for in vivo glucose sensing in skin

A graphite rod 13 (Figure 2) with an oxidised surface, 30 mm long × 0.9 mm diameter is glued with epoxy resin into a nylon tube 14 25 mm long, 0.9 mm inside diameter, 1,3 mm outside diameter. The end 15 of the electrode is dipped into a solution of dimethyl ferrocene, (10 mg/ml) in toluene, and the solvent is then allowed to evaporate.

The end 15 of the electrode is placed into a solution of water soluble DCC (25 mg/ml) in acetate buffer, pH 4.5 for 1 hour. It is then rinsed, in buffer only, for 5 minutes and thereafter placed in a solution of glucose oxidase (10 mg/ml) in acetate buffer, pH 5.5, for 1½ hours before again rinsing in buffer. The tip of the

electrode 15, with the layers of dimethyl ferrocene and immobilised enzyme is then dipped into a solution of cellulose acetate dissolved in acetone/N,N-dimethylformamide and put into ice water for several minutes, to give a protected and stable electrode.

This electrode was connected to a potentiostat, together with a suitable counter electrode and calomel reference electrode and placed in a solution containing glucose. The potential of the working electrode is kept at +100 mV to 300 mV relative to the calomel electrode, i.e. as low as possible to avoid oxidation of potentially interfering substances. A current is produced which is proportional to the glucose concentration. The time for 95% of response is less than 1 minute and the electrode gives a near linear response over the range 0—32 mM glucose, as shown in Figure 3. Slow loss of activity of ferrocene (due to slow loss of ferricinium ion) can be minimised by keeping the electrode at a potential of −100mV vs. a standard calomel electrode when not in use.

Figure 4 shows in section an electrode structure in which an electrode (references as in Figure 2) of much smaller size is held within a hypodermic needle 16 plugged at its point 17 but with side windows 18 for passage of blood or other body fluid. The small size of such an electrode and its linear response over a large range of glucose concentrations makes it possible to use the electrode for *in vivo* glucose determination on both severely diabetic and normal individuals.

Comparative example 6

Glucose Oxidase/Ferrocene
In vitro sensor

A carbon rod 19 (Figure 5 Ultra carbon, grade U5, 6 mm × 15 mm) with a metal connector 20 secured in one end was sealed in glass tubing 21 (borosilicate, 6 mm i.d. × mm) with an epoxy resin (Araldite, Trade Mark, not shown). The exposed surface at 22 was polished with emery paper and washed with distilled water. The entire rod was heated in an oven for 40 h at 200°C to give an oxidised surface at 22.

15 ul of ferrocene (20 mg/ml in toluene) was pipetted onto the oxidised surface and allowed to dry completely. The rod was then placed in 1 ml of water-soluble DCC (25 mg/ml in 0.1 M acetate buffer, pH 4.5) for 80 min at room temperature. The rod was then washed in 0.2 M acetate buffer, pH 9.5 and placed in a glucose oxidase solution (Sigma type X, 12.5 mg/ml) for 1½ hours at room temperature. It was finally washed with water with a pH 7 buffer containing 0.2 g/l glucose) and stored at 4°C.

The characteristics of the above electrode were determined in a nitrogen-saturated buffer solution (0.2 M sodium phosphate, pH 7.3) and are shown in Figure 6. The curve is linear from 2 to 25 mM glucose and reaches saturated current at 100 mM in glucose.

In separate tests with an air-saturated buffer at 8 mM glucose the current was measured as being at least 95% of that produced in the nitrogen-saturated buffer.

Response time was also measured, being the time taken to achieve 95% of maximum current for the given concentration. With the nitrogen-saturated buffer an electrode as described above had a response time of 24 seconds at 2 mM glucose and 60 seconds at 6 mM glucose. With the same buffer, such an electrode modified by a cellulose acetate membrane coating (produced as in Example 7) gave response times of 36 seconds (2 mM) and 72 seconds (6 mM). With blood, this modified electrode gave response time of 36 seconds (blood with a known 2 mM glucose content) and 72 seconds (blood at a known 6 mM glucose content).

Electrodes as above were stored in 20 mM sodium phosphate, pH7 for 4 weeks at 4°C as a stability test and thereafter re-examined as above. The results were within 10% and usually within 5% of results with a freshly made electrode.

Comparative example 7

Glucose Dehydrogenase/Ferrocene

A stiff carbon paste was made up from 1.6 g of Durco activated charcoal and 2.5 ml of liquid paraffin. A pasteur pipette of 6 mm internal diameter was blocked 2 mm from its wide end by a silver disc to which a connecting wire was soldered. The space between the disc and the end of the pipette was filled with the carbon paste and the surface of the paste was polished with paper until smooth and even.

A single 20 microlitre drop of a toluene solution of ferrocene (20 mg/ml) was placed on the smooth surface and allowed to spread and evaporate to leave a film of the ferrocene.

A further drop of 25 microlitres of bacterial glucose dehydrogenase solution as obtained in Example 1, containing between 1 and 10 mg of protein per ml, was placed on this ferrocene surface and allowed to spread.

A cover of dialysis membrane was secured over the so-coated end of the electrode by a tight-fitting O-ring.

Comparative example 8

Glucose Dehydrogenase/Ferrocene

The procedure of Example 7 was repeated but using as electrode the same carbon paste packed into the space defined between the end of a length of nylon tubing and a stainless steel hypodermic needle shaft inserted therein terminating 2 mm short of the tubing end, so as to define a small electrode body. The electrode was further fabricated using only 5 microlitres of the ferrocene solution and 1 microlitre of the enzyme solution.

Comparative example 9

Glucose Dehydrogenase/Ferrocene

The procedure of Example 8 was repeated using as an electrode a solid carbon rod (Ultracarbon grade U5 6 mm diameter) within a Pyrex glass tube 3 cm long and 6 mm internal diameter connected to a stainless steel hypodermic shaft, giving a construction similar to that shown in Figure 5. The end of the carbon rod was polished smooth with emery cloth and aluminium oxide powder prior to the application of the ferrocene solution.

Comparative example 10

Glucose Dehydrogenase/Ferrocene

A gelatin-entrapped glucose dehydrogenase was prepared by mixing at 37°C, 25 mg gelatin, 0.5 ml of the glucose dehydrogenase solution as described in Example 9 and 2.5 microlitres of N,N,N',N'-tetramethylethylenediamine ("TEMED"). After complete dissolution of the gelatin, 200 microlitres of the solution was spread over an area of 2 cm^2 and allowed to dry under a stream of cold air.

A disc of 0.25 cm^2 area was then used instead of the drop of enzyme solution in Example 8.

Comparative example 11

Glucose Dehydrogenase/Ferrocene

Example 10 was repeated using a disc of the gel of 1 mm^2 area and applying it instead of the drops of enzyme solution in the construction of example 10.

The results obtained from the electrodes described in Examples 7—11 are all similar, and show a very specific electrode of low oxygen sensitivity. By way of example the electrode of Example 10 was calibrated and gave the results shown in Figure 7.

Examples 12—24

D.C. cyclic voltammetry was used to demonstrate the ability of a ferrocene compound (usually ferrocenemonocarboxylic acid) to generate and enhance anodic current in the presence of each of the following enzymes, together with their respective substrates:

TABLE 2

Enzyme	Substrate
Flavoproteins	
Pyruvate Oxidase	Pyruvate
L-Amino Acid Oxidase	L-Amino Acids
Aldehyde Oxidase	Aldehydes
Xanthine Oxidase	Xanthines
Glycolate Oxidase	Glycolate
Sarcosine Oxidase	Sarcosine
PQQ Enzymes	
Methanol Dehydrogenase	Methanol and other Alkanols
Haem-Containing Enzymes	
Lactate Dehydrogenase (Yeast Cytochrome b_2)	Lactate
Horseradish Peroxidase Yeast Cytochrome c Peroxidase	Hydrogen Peroxide
Cuproproteins	
Galactose Oxidase	Galactose
Other enzyme	
Carbonmonoxide Oxidoreductase	Carbon Monoxide

In each case, the enzyme/mediator system gave an enhanced anodic current, indicative of the enzyme-catalysed reaction. Second order homogeneous rate constants calculated from the data thus obtained indicated that the ferrocene compound effectively mediated the enzyme-electrode electron transfer in a manner suitable for construction of an electrode assay system.

A representative protocol for the cyclic voltammetry is as follows:

Example 25

a) Electrochemical instrumentation

D.C. cyclic voltammetry, which is a controlled potential electrochemical method, is based upon the maintenance within a cell of the potential of the working electrode (WE) with respect to a reference electrode (RE) by making a current pass between the working and counter electrode (CE). Figure 1 shows the circuit that was used which incorporates two operational amplifiers. These were built into an Oxford Electrodes potentiostat. Current-potential curves were recorded with a Bryans X—Y 26000 A3 chart recorder. Applied potential = V in; current = V out/R.

A 380Z micro-computer (Research Machines Ltd), interfaced to a potentiostat *via* digital-to-analogue and analogue-to-digital converters, was used for the potential step methods. The potentiostat incorporates a multiplexer which facilitates both switching and monitoring of more than one working electrode.

b) Cells and Electrodes

D.C. cyclic voltammetry experiments were performed using a two compartment cell, with a working volume of *ca.* 1 ml, of the configuration shown in Fig. 2, i.e. where the two compartments are placed in communication by Luggin capillary 31 (Figure 2).

In addition to a 4 mm diameter working electrode 32 made of gold (platinum and pyrolytic graphite were also tried successfully), the cells contained a 1 cm^2 platinum gauze counter electrode 33 and a saturated calomel electrode, 34 type K401 (supplied by V. A. Howe Radiometer Electrodes) accurate in the range −10°C to 60°C, as reference. All potentials are referred to the saturated calomel electrode (SCE), which is +241 mV at 20°C versus the normal hydrogen electrode (NHE).

Working electrodes were polished before each experiment using an alumina-water paste on cotton wool and then washed with deionised water. Alumina with a particle size *ca.* 0.3 µm, was supplied by BDH.

c) Temperature control

Electrochemical experiments were performed under thermostatic control by using a Churchill chiller thermocirculator connected to a water bath into which the electrochemical cell was placed.

d) Spectrophotometric measurements

All optical spectra were recorded with a Pye-Unicam SP8 200 spectrophotometer with the sample and reference solutions in matched quartz micro-cuvettes of path length 1 cm.

e) Water purification

Where possible, all solutions were prepared with water purified by a sequence of reverse osmosis, ion exchange and carbon filtration using a combined Milli-RO4 and Milli-Q system supplied by Millipore Ltd.

f) Ultrafiltration and diafiltration

Ultrafiltration and diafiltration of proteins were performed by using the appropriately sized Amicon cell with a suitable Diaflo membrane.

g) Fast protein liquid chromatography

Protein purifications were performed using an FPLC (Trade Mark) system supplied by Pharmacia. This incorporated two pumps controlled by a gradient programmer operated in conjunction with a single wavelength UV-monitor (λ = 260 nm) and an automatic fraction collector. Analytical and preparative ion-exchange columns were also supplied by Pharmacia.

h) Materials

The flavo-proteins pyruvate oxidase, xanthine oxidase, sarcosine oxidase, lipoamide dehydrogenase and glutathione reductase were supplied by Boehringer and stored at −20°C. The respective concentrations of the flavo-proteins are expressed in terms of the amount of catalytically-active flavin.

Carbonmonoxide oxidoreductase was isolated from *Pseudomonas thermocarboxydovorans* by Dr. J. Colby, Biochemistry Department, Sunderland Polytechnic and supplied at a concentration of 8.6 mg ml^{-1}, in phosphate buffer containing 50% ethanediol as a stabilizer. Before use, the enzyme was dialysed against 20 mM Tris-HCl (pH 7.5) at 4°C, and purified by FPLC using an analytical Mono-Q (Trade Mark) column. The enzyme was loaded on to the column at a concentration of 1.0 mg ml^{-1} in 20 mM Tris-HCl pH 7.5 (buffer A) and eluted with a linear ionic strength gradient using buffer B (A + 1.0 M KCl). Carbon monoxide oxido-reductase eluted as one major peak at an ionic strength equivalent to 35% buffer B, as shown in Figure 10.

Purification of the quino-protein alcohol dehydrogenase (EC 1.1.99.8) is described above. Lactate dehydrogenase (EC 1.1.1.27) and isocitrate dehydrogenase (EC 1.1.1.42) were supplied by Boehringer.

Sodium lactate, sodium isocitrate, sarcosine, sodium pyruvate, xanthine, cholesterol, potassium oxalate, choline, reduced nicotinamide adenine dinucleotide (NADH) and reduced nicotinamide adenine dinucleotide phosphate (NADPH) were supplied by Boehringer. Carbon monoxide was supplied by BOC. Ferrocene monocarboxylic acid was supplied by Fluorochem. Horse heart cytochrome *c* type VI, was supplied by Sigma and purified before use to remove deamidated forms.

i) Electrolytes

All experiments used 100 mM Tris-HCl buffer pH 7.0, except those involving oxalate oxidase which used 100 mM succinate buffer pH 3.0, and those with alcohol dehydrogenase which used 100 mM borax-NaOH, pH 10.5, containing 14 mM NH_4Cl.

j) Electrochemical experiments

All experiments used the electrochemical cell of Figure 9 incorporating a 4 mm disc pyrolytic graphite working electrode, except in experiments on lipoamide dehydrogenase and glutathione reductase where a 4 mm disc gold electrode was used. In experiments where cytochromes *c* was investigated with carbon monoxide oxido-reductase, a (4,4'-pyridyl)-1,2-ethene modified gold electrode was used.

D.C. cyclic voltammetry experiments are performed in argon-saturated solutions using the following protocol. Firstly, the reversible electrochemistry of ferrocene monocarboxylic acid (200 µM) in a suitable electrolyte is established by recording voltammograms at different scan rates (v = 1—100 mVs^{-1}) over the potential range 0—400 mV. Substrate is then added to the cell, typically to a final concentration of 10 mM and always in excess of the Michaelis-Menten constant for the enzyme. A set of voltammograms are recorded to assess the effect of the substrate upon the electrochemistry of the mediator. Enzyme is then

added to the final concentrations in the range 10—100 μM. If an enhanced anodic current is obtained, and the dependence of the current function upon the scan rate was indicative of a catalytic reaction, the experiment is repeated adding the substrate as the final component to ensure that the reaction was dependent upon the presence of substrate.

Under the conditions that were used, none of the substrates interfered with the electrochemistry of the ferrocene. Over the range 0—400 mV vs SCE, none of the substrates or enzymes exhibited any direct electrochemistry.

Comparative examples 26—31

The above described cyclic voltammetry was used to demonstrate the electron-transfer capability of a variety of ferrocene compounds listed with a glucose/glucose oxidase system:

TABLE 3

Rates of glucose oxidase oxidation measured at pH 7 and 25°C (examples 24—29)

Ferrocene derivative	E°/mV vs SCE	10^{-3}ks/$M^{-1}s^{-1}$
1,1'-dimethyl-	100	44
ferrocene	165	15
vinyl-	250	18
carboxy-	275	115
1,1'-dicarboxy-	385	15
trimethylamino-	400	300

a) Solution kinetics.

A variety of ferrocene derivatives, Table 3, with a range of potentials (150 to 400 mV vs SCE) were investigated as possible oxidants for glucose oxidase using D.C. cyclic voltammetry. Figure 11 shows at (a) a voltammogram of carboxyferrocene which fulfils electrochemical criterion as a reversible one-electron couple (Δ_p = 60 mV; $i_p/v^{\frac{1}{2}}$ = constant). The addition of glucose alone in solution has no discernible effect upon the voltammogram. However, upon further addition of glucose oxidase to the solution (b) a striking change in the voltammogram occurs. Enhancement of the anodic current is observed. The data shown in Table 3, indicate that the oxidized form of all ferrocene derivatives investigated act as a rapid oxidant for the enzyme, with rates of reaction comparable to that of the natural electron acceptor, molecular oxygen, which has a value of $k_s = 10^5\ M^{-1}.s^{-1}$.

Although all the ferrocene derivatives shown in Table 3 lead to the effective electrochemical oxidation of glucose *via* glucose oxidase, other criteria are important in designing a practical enzyme electrode. The solubility of the reduced form of the ferrocene derivative in aqueous media must be low to aid entrappment within the electrode; the oxidised form should be stable at physiological pH; the formal potential should be low to obviate interference from reduced compounds present in physiological samples. 1,1'-dimethylferrocene provided the best compromise between the constraints imposed by these factors and was chosen for incorporation into the enzyme electrode.

b) Enzyme electrode

Digital simulation techniques have shown that the steady state current for an amperometric enzyme electrode is determined predominantly by the apparent Michaelis-Menten constant, K_M', the membrane permeability, the effective electrode surface area and the enzyme loading factor (concentration per unit volume). Considering the available enzyme immobilization techniques, covalent attachment to a functionalised electrode surface generally gives the most lasting enzyme activity. Additionally, the resulting monolayer coverage is the most appropriate for optimum response characteristics. On this basis, a batch of twenty-four of the prototype glucose enzyme electrodes were constructed as described below and their performance evaluated.

c) Reagents

Glucose oxidase (EC 1.1.3.4 type 2, from *Aspergillus niger*), was supplied by Boehringer Mannheim, had an activity of 274 IU/mg. D-glucose (AnalaR) was from BDH; ferrocene and its derivatives were from Strem Chem. Co. All solutions were prepared from Aristar grade reagents (BDH) in high purity water (Millipore); supporting electrolyte was 0.1 M K_2HPO_4 adjusted to the required pH with $HClO_4$, glucose solutions were stored overnight to allow equilibration of α- and β-anomers. Properties of this enzyme are given in the table below;

TABLE 4

source;	*Aspergillus Niger*
RMM;	186000
Co-factor	2FAD
Co-substrate	Oxygen
Optimum pH	5.6
K_m Glucose	30 nM

d) Biological samples

Heparinised plasma samples from human diabetics were supplied by the Metabolic Unit, Guy's Hospital, London, and had been previously analysed for glucose with a Yellow Springs Instruments, Ohio, glucose analyser.

e) Apparatus

D.C. cyclic voltammetry experiments were performed using a two-compartment cell that had a working volume of 1 ml. In addition to the 4 mm pyrolytic graphite disc working electrode, the cell contained a 1 cm^2 platinum gauze counter electrode and a saturated calomel electrode as reference. (Bourdillon C. et al, J. Amer. Chem Soc *102*, 4231, 1980). All potentials are referred to the saturated calomel electrode (SCE). For D.C. cyclic voltammetry, an Oxford Electrodes potentiostat was used with a Bryans X—Y 26000 A3 chart recorder. The potentiostatically-controlled steady-state current measurements were made using a cell, designed to accommodate up to seven enzyme electrodes, with a working volume of 100 ml with separate compartments for counter and reference electrodes. Current-time curves were recorded with a Bryans Y-t BS—271 recorder. The temperature of the electrochemical cells during experiments were controlled to within ±0.5°C with a Churchill thermocirculator.

f) Construction of the glucose enzyme electrode

Graphite foil 1 mm thick, supplied by Union Carbide was the base sensor. Electrodes were constructed by cutting the graphite into 4 mm diameter discs and sealing into glass rods with epoxy resin. The electrodes were then heated at 200°C in air for 40 hours, allowed to cool, 15 µl of 1,1'-dimethylferrocene (0.1 M in toluene) was deposited on to the surface of the electrode and air-dried. Covalent attachment of the glucose oxidase to the oxidised graphite surface was achieved by a method similar to that described by Bourdillon. The electrodes were placed in 1 ml of a solution of water-soluble 1-cyclohexyl-3-(2-morpholinoethyl)carbodiimide metho-p-toluenesulphonate from Sigma Chem. Co. (0.15 M in 0.1 M acetate, pH 4.5), for 80 mins at 20°C, washed with water and then placed in a stirred solution of acetate buffer (0.1 M, pH 5.5) containing glucose oxidase (12.5 mg/ml) for 90 mins at 20°C. After washing, the electrodes were covered with a polycarbonate membrane (Nucleopore, 0.03 µm) and stored in buffer containing 1 mM glucose at 4°C.

g) Enzyme electrode pre-treatment

After fabrication and prior to experiments, the electrode response was stabilized by continuous operation of the electrode under potentiostatic control at 160 mV in 8 mM glucose over a 10 hours period. Thereafter the electrodes were found to give a more stable response during 100 hours further operation. In 8 mM buffered glucose, the electrodes gave a mean current decrease of 3%±1 over this period. All electrodes which had been modified with glucose oxidase had undergone this pre-conditioning process.

All electrodes gave a linear current response in the range 0.1—35 mM glucose and finally saturated at approximately 70 mM glucose. In the linear region, the electrodes showed a rapid response time reaching 95% of the steady-state current in 60—90 secs. The reproducibility of the electrode construction protocol was investigated by measuring the steady-state current for each electrode in 8 mM glucose. The batch of prototype electrodes gave a mean current response of 7.9 µA with a standard deviation of 2.8.

h) The effect of temperature

The effect of temperature on the enzyme electrode response was studied in the range 10—50°C, and showed the increase in steady state current with increasing temperature, *ca.* 0.2 µA/°C. All electrodes showed similar behaviour. Assuming Arrhenius type behaviour, the absence of maxima in the electrode response, is indicative of the thermal stability of the immobilized enzyme at temperatures up to 50°C. This electrode configuration should be suitable for extended use at normal body temperature. Similar thermal stability was also found with soluble enzyme, the dependence of the second order rate constant upon temperature, giving an activation energy for the reaction of 49.6 KJ Mol^{-1}.

i) Interfering substances

The effects of substances which might interfere with the response of the electrodes, either through direct electrode oxidation, reaction with the mediator, or, inhibition of the enzyme, were examined. Analyses of solutions containing 8 mM glucose, to which metabolites were added to give their normal blood concentrations were carried out. L-ascorbate at a final concentration of 0.13 mM gave a mean increase in current of *ca.* 4.0%.

Particular interfering, or potentially interfering substances are listed in table 5 below. All of the listed substances are substrates for glucose oxidase, however the relative rates of reaction are much lower than that of the primary substrate, glucose. Although experiment showed that the effect on glucose assays of these substances was minimal, it is envisaged that in the absence of glucose the sensor of the present electrode could be employed to assay for any of the listed substrates.

TABLE 5

Substrate	Relative Rate
β-D-Glucose	100
2-deoxy-D-glucose	25
6-methyl-D-glucose	2
D-mannose	1
α-D-glucose	0.6

L-cysteine HCl (0.08 mM), reduced glutathione (0.49 mM), sodium formate (7.35 mM), D-xylose (8.00 mM), α-galactose (7.77 mM) and α-mannose (7.77 mM) did not cause any observable interference to the electrodes response to glucose.

There was however, a mean decrease in the current response of 4.0% when changing from nitrogen-saturated to air-saturated buffer. Whilst interference from oxygen is not surprising, the current decrease occurs as the base electrode was not poised sufficiently positive to re-oxidise the hydrogen peroxide generated by the enzymatic reaction. Operation of the electrode at potentials sufficiently positive to re-oxidize the hydrogen peroxide also leads to increased interference from L-ascorbate.

j) Effect of pH

Since the pH of diabetic plasma samples may vary either through the addition of heparin or loss of carbon dioxide, the effect of pH on the response of the glucose electrode was investigated over the clinically relevant range. The steady-state current of the above-described enzyme electrode is essentially independent of pH. This paralleled the behaviour of the soluble enzyme, where the second order rate constants for all ferrocene derivatives shown in Table 3 were found to be independent of changes in pH in the range pH 6—9. This desirable feature of a non-pH dependent response, is presumably due to the fact that, in contrast with oxygen-mediated glucose enzyme electrodes, no proton transfer is involved in ferrocene oxidation.

Devices such as shown in the Examples offer advantages over most of the enzyme-based sensors currently available. When compared to such sensors prior to dilution steps, the present electrode has an equal or faster response time, the ability to operate under anaerobic conditions, greater oxygen insensitivity (important in blood samples, where oxygen concentration is variable), extended linear range covering the complete physiological range and comparable specificity, stability and ease of manufacture.

The thiol group can be directly or indirectly attached to one ring of the ferrocene structure, e.g. by a lower alkyl group containing 1 to 6 carbon atoms. The simple thiol (ferrocene)-SH can be used, prepared as in J. Chem. Soc. 692 (1958) Knox and Pauson. We have also established that of the alkyl thiols, ferrocenyl thiobutane is valuable i.e. (ferrocene)-C_4H_8—SH. Other more complex thiol-like compounds are possible e.g. 1,2,3-trithia-(3)-ferrocenophane in which the two rings are linked by a chain of sulphur atoms (a mixture of substances with different numbers of chain sulphur atoms is possible).

The gold electrode can be prepared for repeated use e.g. by dipping into solutions of such compounds, so as to link the mediator ferrocene structure to the conductive metal.

Claims

1. An electrode sensor system for sensing the presence of at least one selected component of a mixture of components said sensor system comprising:

at least two electrically conducting means insulated from each other, each of which is in electrical contact with said mixture via an electrically conductive surface.

An enzyme which is a non-oxygen specific flavor protein other than glucose oxidase, a quino-protein other than glucose dehydrogenase, a haem-containing enzyme, a cupro-protein, or carbonmonoxide oxidoreductase,

a mediator compound which transfers electrons between said enzyme and one said conductive surface when said enzyme is catalytically active, said mediator being an organometallic compound which comprises

at least two organic rings, each of which is characterised by at least two double bonds that are conjugated and a metal atom in electron-sharing contact with each of said rings.

2. The system of claim 1 wherein said mediator is confined at said electrically conducting surface.

3. The system of claim 1 wherein said enzyme is confined at said electrically conducting surface.

4. The system of claim 1 wherein said selected component is a substrate for said enzyme-catalyzed reaction.

5. The system of claim 1 wherein said mediator compound is a ferrocene-type compound.

6. The system of claim 5 wherein said ferrocene-type compound is selected from the group consisting of ferrocene; chloroferrocene; methyl-trimethylaminoferrocene; 1,1-dimethylferrocene; 1,1-dicarboxyferrocene; carboxyferrocene; vinylferrocene; trimethylferrocene; polyvinylferrocene; hydroxyethylferrocene; acetoferrocene; and 1,1'-bishydroxymethyl ferrocene.

7. The system of claim 1 wherein said enzyme is selected from the group consisting of pyruvate oxidase, xanthine oxidase, sarcosine oxidase, carbonmonoxide oxidoreductase, glycolate oxidase and L-amino acid oxidase.

8. The system of claim 1 wherein said enzyme is methanol dehydrogenase.

9. The system of claim 1 wherein said metal atom is iron.

10. The system of claim 1 wherein said metal atom is ruthenium.

11. A sensor as claimed in claim 1 in which the electrode is made of a material chosen from silver, carbon particle paste and solid carbon.

12. The sensor system of claim 1 with implantation means suitable for implantation in a human subject.

13. A sensor system of claim 1 wherein said mediator compound transfers electrons from said enzyme to said conductive surface.

14. The system of claim 1 in which the enzyme is chosen from the group consisting of lactate dehydrogenase, yeast cytochrome c peroxidase and horseradish peroxidase.

15. The system of claim 1 in which the enzyme is galactose oxidase.

16. The system of claim 1, wherein the mediator is covalently bond to the electrode and/or the enzyme.

Patentansprüche

1. Ein Elektroden-Meßwertfühlersystem zum Messen der Anwensenheit mindestens eines ausgewählten Inhaltsstoffs einer Mischung von Inhaltsstoffen, wobei dieses Meßwertfühlersystem umfaßt:

mindestens zwei elektrische leitende, gegeneinander isolierte Mittel, von denen jedes über eine elektrisch leitende Oberfläche mit der genannten Mischung in elektrischen Kontakt steht;

ein Enzym, bei dem es sich handelt um ein nichtsauerstoffspezifisches Flavoprotein mit Ausnahme von Glukose-Oxidase, ein Chinoprotein mit Ausnahme von Glukose-Dehydrogenase, ein Häm enthaltendes Enzym, ein Cuproprotein oder Carbonmonoxidoxidoreduktase;

eine Vermittlermasse, die Elektronen zwischen dem genannten Enzym und einer leitenden Oberfläche überträgt, wenn dieses Enzym katalytisch aktiv ist, wobei der Vermittler eine organometallische Verbindung ist, die umfaßt:

mindestens zwei organische Ringe, von denen jeder gekennzeichnet ist durch mindestens zwei konjugierte Doppelbindungen und ein Metallatom in elektronenanteiligem Kontakt mit jedem dieser Ringe.

2. System nach Anspruch 1, bei dem der Vermittler an der elektrisch leitenden Oberfläche eingeschlossen ist.

3. System nach Anspruch 1, bei dem das Enzym an der elektrisch leitenden Oberfläche eingechlossen ist.

4. System nach Anspruch 1, bei dem der ausgewählt Inhaltsstoff ein Substrat für enzymkatalysierte Reaktion ist.

5. System nach Anspruch 1, bei dem die Vermittlermasse eine Verbindung des Ferrocen-Typs ist.

6. System nach Anspruch 5, bei dem die Verbindung des Ferrocen-Typs ausgewählt ist aus der Gruppe, die aus Ferrocen, Chlorferrocen, Methyl-trimethylaminoferrocen, 1,1-Dimethylferrocen, 1,1-Dicarboxyferrocen, Carboxyferrocen, Vinylferrocen, Trimethylaminoferrocen, Polyvinylferrocen, Hydroxyferrocen, Essigferrocen und 1,1-bis-Hydroxymethylferrocen besteht.

7. System nach Anspruch 1, bei dem das Enzym ausgewählt wird aus der Gruppe, die aus Pyruvatoxidase, Xantinoxidase, Sarcosinoxidase, Carbonmonoxidoxidoreduktase, Glycolatoxidase und L-Aminosäureoxidase besteht.

8. System nach Anspruch 1, bei dem das Enzym Methanoldehydrogenase ist.

9. System nach Anspruch 1, bei dem das Metallatom Eisen ist.

10. System nach Anspruch 1, bei dem das Metallatom Ruthenium ist.

11. Meßfühler nach Anspruch 1, bei dem die Elektrode aus einem Werkstoff besteht, der aus Silber, Kohlenstoffteilchenpaste und massivem Kohlenstoff ausgewählt ist.

12. Meßfühlersystem nach Anspruch 1, mit geeigneten Implantationsmitteln zur Implantation in einem Menschen.

13. Meßfühlersystem nach Anspruch 1, bei dem die Vermittlerverbindung Elektronen vom genannten Enzym zur genannten leitenden Oberfläche überträgt.

14. System nach Anspruch 1, bei dem das Enzym aus der Gruppe gewählt ist, die aus Lactatdehydrogenase, Hefectyochromperoxidase und Meerrettichperoxidase besteht.

15. System nach Anspruch 1, bei dem das Enzym Glactoseoxidase ist.

16. System nach Anspruch 1, bei dem das Vermittler kovalent an die Elektrode und/oder das Enzym gebunden ist.

Revendications

1. Système de détecteur à électrodes pour déceler la présence d'au moins un constituant choisi, faisant partie d'un mélange de constituants, ledit système détecteur comprenant au moins deux moyens électriquement conducteurs, isolés l'un de l'autre et dont chacun est en contact électrique, par l'intermédiaire d'une surface électriquement conductrice, avec ledit mélange,

une enzyme, qui est une flavoprotéine ne réagissant pas spécifiquement à l'oxygène, autre que de la glucoseoxydase, une quinoprotéine autre que de la glucose déshydrogènase, une enzyme contenant de l'hème ou une cuproprotéine ou une oxydoréductase de monoxyde de carbone,

un composé médiateur, qui transfère des électrons entre ladite enzyme et l'une desdites surfaces conductrices lorsque ladite enzyme est catalytiquement active, ledit médiateur étant un composé organo-métallique qui comprend au moins deux noyaux organiques, dont chacun est caractérisé par la présence d'au moins deux doubles liaisons qui sont conjuguées et par la présence d'un atome de métal en contact, avec partage d'électron(s), avec chacun desdits noyaux.

2. Système selon la revendication 1, dans lequel ledit médiateur est confiné à ladite surface électriquement conductrice.

3. Système selon la revendication 1, dans lequel ladite enzyme est confinée à ladite surface électriquement conductrice.

4. Système selon la revendication 1, dans lequel ledit constituant choisi est un substrat pour ladite réaction catalysée par une enzyme.

5. Système selon la revendication 1, dans lequel ledit composé médiateur est un composé de type ferrocène.

6. Système selon la revendication 5, dans lequel ledit composé de type ferrocène est choisi parmi du ferrocène; du chloroferrocène; du méthyl-triméthylaminoferrocène; le 1,1-diméthylferrocène; le 1,1'-dicarboxyferrocène; du carboxyferrocène; du vinylferrocène; du triméthylaminoferrocène; du polyvinylferrocène; de l'hydroxyéthylferrocène; de l'acétoferrocène et le 1,1'-bishydroxyméthylferrocène.

7. Système selon la revendication 1, dans lequel ladite enzyme est choisie parmi de la pyruvate oxydase, de la xanthine oxydase, de la sarcosine oxydase, de l'oxydoréductase de monoxyde de carbone, de la glycolate oxydase et de la L-aminoacide oxydase.

8. Système selon la revendication 1, dans lequel ladite enzyme est de la méthanol déshydrogénase.

9. Système selon la revendication 1, dans lequel ledit atome de métal est le fer.

10. Système selon la revendication 1, dans lequel ledit atome de métal est ruthénium.

11. Détecteur selon la revendication 1, dans lequel l'électrode est en une matière choisie parmi l'argent, une pâte à particules de carbone et du carbone solide ou massif.

12. Système de détecteur selon la revendication 1, comportant un moyen d'implantation convenant pour son implantation dans un sujet humain.

13. Système de détecteur selon la revendication 1, dans lequel ledit composé médiateur transfère des électrons de ladite enzyme vers ladite surface conductrice.

14. Système selon la revendication 1, dans lequel l'enzyme est choisie parmi de la lactate déshydrogénase, de la peroxydase de cytochrome de levure et de la peroxydase de raifort.

15. Système selon la revendication 1, dans lequel l'enzyme est de la galactose oxydase.

16. Système selon la revendication 1, dans lequel médiateur est lié par covalence à l'électrode/ou à l'enzyme.

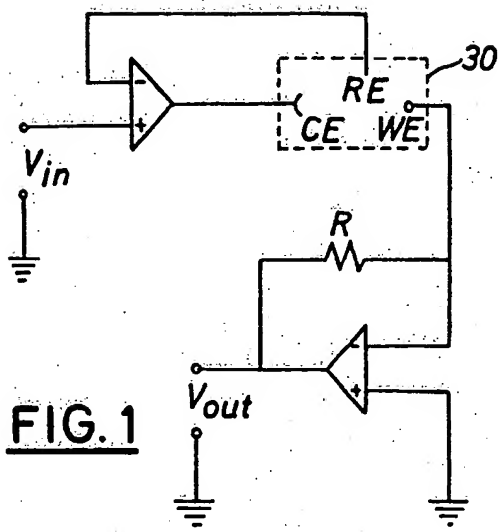

FIG. 1

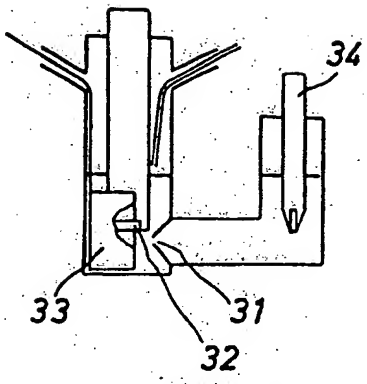

FIG. 2

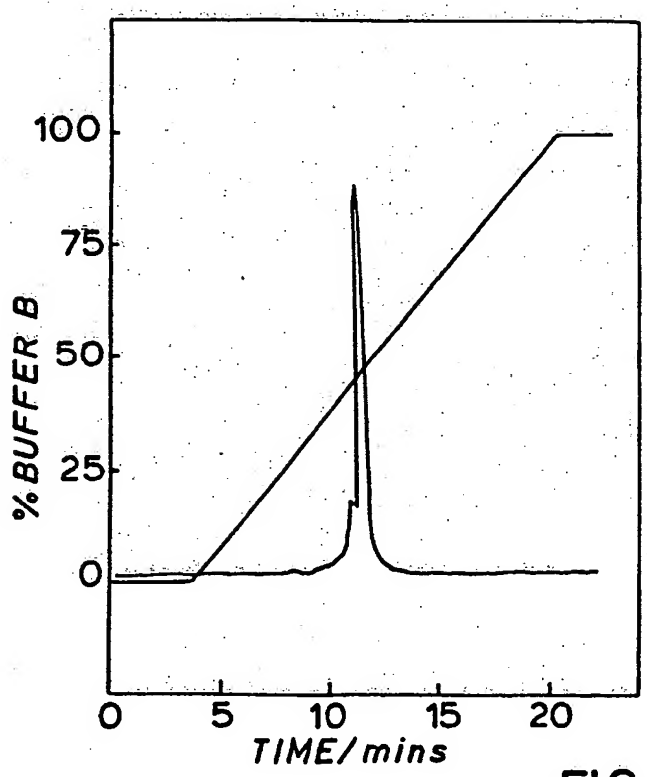

FIG. 3

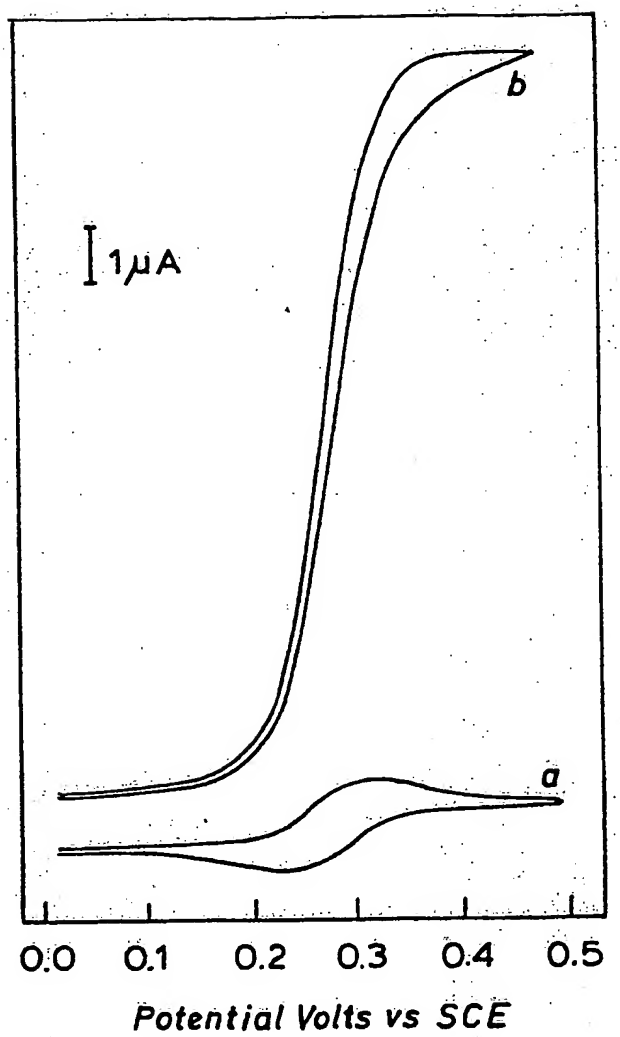

FIG. 4